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Assessment of groundwater infiltration and recharge. A case of Yala catchment, Kenya

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ABSTRACT

The Yala catchment was projected to experience water deficit by 2030 due to declining discharge levels in both surface and groundwater systems, exacerbated by rainfall variability, climate change, and high-water demand. This study investigated the hydrogeological dynamics of the catchment, focusing on volumetric soil moisture (VSM), soil temperature, and infiltration-recharge processes, to develop a decision-making tool for sustainable water resource management. Utilizing ArcGIS, statistical analysis, and regression modeling, the research analyzed near-surface soil moisture dynamics and their implications for groundwater recharge. Results indicates a subtle soil wetting phenomenon (ΔVSM ≈ 0.9%), with VSM increasing from 4% to 5.3% and stabilizing at 4.25%, coupled with modest soil temperature variations (~17.84–21.83°C). These findings suggest initial near-surface infiltration conditions, with soil moisture remaining below field capacity (~0.25 m^3/m^3 for loam), limiting gravitational drainage. Statistical regression yielded an R^2 of 0.72, confirming the reliability of the analysis. The study underscored the critical role of near-surface soil moisture dynamics during the first 2000 minutes of precipitation in determining infiltration rates and recharge potential. To achieve a comprehensive understanding of hydrogeological processes, the research recommended investigations to assess water table responses to recharge. This methodology is replicable in other catchments with analogous hydrogeological characteristics, providing a framework for mitigating water deficits and enhancing sustainable water resource management.

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1. Introduction

Yala catchment is a critical water resource in Kenya, but it faces a projected water deficit by 2030 due to declining discharge levels in surface and groundwater resources as projected by the national water master plan (Government of Kenya, 2013). Water demand from groundwater was projected to increase gradually due to impact on the resource including demographic changes, climate change impacts, and depletion of surface water resources, urbanization, industrialization, and pressure for food security (Davamani et al., 2024).

These impacts increase groundwater vulnerability by raising temperatures, causing irregular rainfall and drought, leading to declining groundwater levels and storage. Precipitation is the most critical input for ground water, this was observed in a study in the same catchment where precipitation was increasingly experiencing impacts of climate change including rainfall variability, exacerbated by rainfall variability, climate change, and high water demand. Inadequate infiltration and recharge further aggravate the situation, threatening water availability for ecosystems, agriculture, and human consumption (Miima et al., 2025). The water resources engineering aligned sectors including agriculture, irrigation, civil engineering and environmental sciences are also prone to this impacts (Ehiomogue et al., 2021). The nature of groundwater flow in the catchment is dynamic with complex factors involved. This factors controls infiltration including soil properties, input of water into soils, redistribution of water within soils, deep percolation down to groundwater, surface runoff and flow occurrence with respect to time (Ayona et al., 2020). To understand this phenomenon, the relationship between the ground

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surface and the vadose zone could be reliably predicted in the catchment from the selected hydrological relevant aspects, it was observed that, the complexity of any watershed compels one to use simplification while conducting the study depending on the problem being dealt with in the sub-areas of the watershed and the contents and spatial relations that are considered as relevant in each case (Kiluva et al., 2022). In a regions with shallow water table, infiltrated water reaches the ground relatively fast through the vadose zone and an individual rainfall event yields quick response to infiltration (Waswa & Lorentz, 2019). This is dependent on the soil media condition at the time before or at the time of the storm event. This condition generates variable spatial infiltration, percolation and recharge levels. Some flow responses are transient and discrete in nature (Waswa & Lorentz, 2019).

Infiltration has attracted increasing attention from agricultural, irrigation and water scientists and engineers considering its fundamental role in agriculture, irrigation, surface and subsurface hydrogeology. Infiltration and recharge models make use of some factors in their characterization including physical properties of soils; the initial soil water content, soil texture, soil structure, hydraulic conductivity and vegetation and function of water infiltration (Mishra et al., 2003). Physically based models considers the soil hydraulic and physical properties within the soil profile, such as hydraulic conductivity, soil moisture, gradient, and the wetting profile (Bhattacharya & Michael, 2010). Empirical models on the other hand considers the estimated curve fitting parameters that better reflect the effect of differences in surface conditions as long as parameters are calibrated separately for those different conditions (Turner, 2006). A study estimated groundwater recharge using soil moisture monitoring, demonstrated how soil moisture sensors (like TMS4) could quantify recharge by tracking moisture movement to deeper layers. The key findings were that prolonged high VSM (>48 hours) at 30–50 cm depth indicates effective recharge (Scanlon et al., 2002). Bhattacharya and Michael (2010) estimated groundwater recharge with a practical guide linking infiltration rates (from sensors) to recharge calculations and concluding that recharge = Infiltration rate × Area × Time, minus E.T. losses. Reynolds et al. (2002) in their research, provided methods to link volumetric soil moisture (VSM) measurements to infiltration rates and reported infiltration rates of 15 mm/hr. for soils different conditions and soil textures. Catchment environmental conditions including temperature and weather also influences infiltration and recharge. Reynolds et al. (2002) emphasized the importance of soil properties and environmental conditions in determining water movement within a soil profile. This aspects are fundamental in the analysis of initial near surface soil water dynamics in a catchment. The study by Bracken et al. (2013), observed that soil water content and the pattern distinguishes facts regarding the flow of water through soil profile and different soil states including the soil filed capacity, infiltration capacity, capillarity among others which are fundamental in the stages of water flow within the hydrogeological system. On the other hand, McNamara et al. (2005) concluded that once the dry soil barriers become wetter, lateral flow occurs, and soil water then directly flows to the downstream water.

Various analytical and semi-empirical models' and techniques have been advanced in this respect to address the challenges of infiltration and ultimately recharge of water to subsurface layers. This models as reviewed by Youngs (1995) including infiltration model which was the first physically-based model developed accounting for many variables and found to apply directly Darcy's law, to derive infiltration equation for arbitrary rainfall rates, and presented an analytical infinite-series solution to the water content based on Richard's equation for the case of vertical infiltration, Kostiakov's model proposed a simple empirical infiltration equation based on curve fitting from field data and finally Horton's model in early 1930s to 1940s was among the first to ground infiltration models.

This study utilized regression analysis and Horton model which is among the best-known models in hydrogeology to investigate infiltration process (Horton, 1940) recognized that infiltration capacity decreased with time until it approached a minimum constant rate. Horton attributed this decrease in infiltration primarily to factors operating at the soil surface rather than to flow processes within the soil which was critical to Horton's view on the idea of infiltration capacity (Horton, 1939). The research established that, as the soil wets and dries, the rate at which water can infiltrate into the soil will change, but that at any point in time there will be a limit, the infiltration capacity, that will be the maximum rate at which rain falling on the soil surface can infiltrate (Horton, 1940). Further, the research advanced that rainfall falling at rates less than the infiltration capacity of the soil would all infiltrate and, therefore, that it was important to distinguish between the terms infiltration rate and infiltration capacity (Horton, 1939).

Basing on the available research knowledge advanced in other catchments and regions, this study therefore investigates the hydrogeological dynamics with respect to Yala catchment, focusing on volumetric soil moisture (VSM), soil temperature, and infiltration-recharge processes, to develop a decision-making tool for sustainable water resource management.

2. Methodology

2.1. The Study Area

The area of study was Yala catchment located within Lake Victoria North Catchment in Kenya as shown in the map in Fig. 1. The catchment experiences equatorial climate with long rains experienced from the months of March to May, short rains from the months of September to November and with an average annual precipitation ranges between 850 mm and up to 2,000 mm spatially distributed across the catchment, whereas the

temperatures ranges from 14ºC to 32ºC with the driest and hottest months being from December to February,.

2.2. Catchment Delineation

The catchment was delineated using ArcGIS tool and the digital elevation model (DEM) developed with a grid size covering the study area created by digitizing the topographic map of the area as shown in Fig. 1. The catchment boundary, the spatial topographic levels, the river boundary, drainage pattern including other boundary conditions in the catchment were established as shown in the catchment Digital Elevation Model (DEM) in Fig. 1.

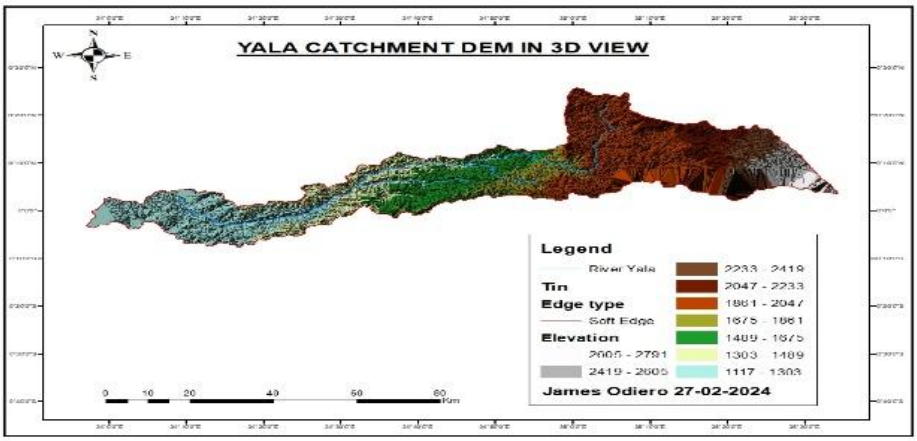


Fig. 1: DEM of Yala Catchment

2.3. Catchment Environment

2.3.1. Vegetation

In the catchment vegetation was extracted and calculated with ArcGIS map using raster tool to quantify, extract, and estimate vegetation coverage in terms of percentages. The Crops accounted for 85%, Evergreen forest, trees-berbercious savanna and plantations cover being 11%, flood or marshy areas 1% and the remaining 3 % was houses and paved areas.

2.3.2. Soils Properties

In this study, the soil texture classification were established based on the percentages of sand, silt and clay using soil sampling and analysis techniques and the classification graph applied to classify the soil in the catchment. The soil field soil information was also corroborated with research by Ayona et al. (2020) Table 1 presents the physical properties of soil in Yala catchment.

Table 1: Physical properties of soil in the catchment

Horizon	Depth(cm)	Particle size distribution			Textural class	Silt/clay ratio
		Sand	clay	silt		
1	0-20	48	40	12	SC	0.3
2	20-63	40	52	8	C	0.15
3	63-115	32	58	10	C	0.2
4	115-150	42	50	8	C	0.2

The catchment soil texture indicated variable textures within their profiles indicative of lithological discontinuity as presented in Table 1. This was consistent with research by Ayona et al. (2020), that the sand content decreased gradually with depth as the proportion of finer particles increased. Soil texture is the most stable physical characteristic of soils which influences several other soil properties including the structure, soil moisture availability, erodibility, root penetration and soil fertility. This is because texture is a composite of the coarse fraction (sand) and the finer fractions (silt and clay) and an increase or decrease in one component imparts the opposite effect on the others and hence affects physicochemical properties of the soils (Karuma, 2019).

2.3.3. Catchment Hydrology

The main river flow in the area is Yala River with tributaries in the upper mid and lower catchment including the Makong River on the upper reaches, Garagoli River, Edzava River and Zaaba River drains the mid-block of the catchment. These rivers flows from east to west and drains into Lake Victoria. The topography map of the area shows altitude levels of the catchment with 2,791m being the highest and 1,117m being the lowest towards Lake Victoria. The length of river Yala is approximately 219km (Wanjala et al., 2024).

2.4. Data Collection

The secondary rainfall data from meteorological department in Kakamega and Vihiga included: precipitation, temperature, and evapotranspiration and evaporation data from 1923 to 2023.

Primary data for soil water was collected in three sites using TMS 4 soil sensors. The parameters collected included temperature and soil moisture. The sensors were placed in areas with eucalyptus and grassland cover to provide a representative of catchment vegetation environment. The sensors collected data with temperature ranging from -60 to +85°C. The lolly manager applications provided data viewer platform for recording, monitoring and data output from the sensors.

The sensors provided the volumetric soil moisture (VSM) for the catchment.

2.5. Catchment Precipitation Analysis

Precipitation (Pi) was considered as key input to the ground water regime and rational method was used to calculate average precipitation as outlined in Eq. 1.

$$\boldsymbol{Pave} = \sum_{n=1}^{m} \left(Pi \frac{Ai}{A} \right) \quad (1)$$

Where: Pave= Average precipitation the polygon area

Pi = Measured precipitation

Ai = The polygon area

A = The total area of the catchment

Other parameters considered included evaporation, evapotranspiration, and runoff. Thiessen polygon method was used to derive the polygon specific rainfall average for the entire catchment. The specific infiltration levels were calculated for individual polygon and an average precipitation of the catchment was generated. The following algorithm was adopted to generated infiltration;

$$\Sigma\, inf = \sum_{n-1}^{n} \big((Pi) - (Ev) - (Et) - (Ic) - (Roff) \big) \quad (2)$$

Where: Inf = Infiltration, Pi = Precipitation, Ev = Evaporation, Et = Evapo-transpiration, Ic = Interception, R_off = Run-off. The equation was adopted from Healy (2010).

Volumetric soil moisture and temperature analysis was done using the TMS4 soil sensors. The gauging stations were mapped into Thiessen polygons using Arc Map where each polygon had a gauging station and borehole source.

2.6. Infiltration and Recharge Analysis

Infiltration capacity is the maximum level at which a given soil absorbs water. Catchment infiltration capacities was done by analysis of soil water measurement (Horton, 1940). This research utilized data from the TMS 4 sensors and used the Robert .E. Horton's equation as outlined in Eq. 3.

$$F_P = F_c + (F_0 - F_c) * e^{-kt} \quad (3)$$

Where: F_p = Infitration capacity at any time, t, F_0 = Initial Infiltration capacity (at t=0), F_c = Final steady state Infiltration capacity, K = Horton's decay coefficient, and F_P = Infiltration capacity, which is the maximum rate at which a given time, can absorb water, F=fp when i≥fp, F=i when i<fp and i is the intensity of precipitation.

In reference to Eq. 2, Infiltration was established by adding evapotranspiration, evaporation and run off and then subtracting the total from precipitation. The infiltration from the upper vadose zone percolating to the phreatic zone is considered recharge. The surface and soil water dynamics determines the ground water recharge through the vadose zone. Eq. 4 was used to generate recharge.

$$Re = \sum(P) - \sum(\mathrm{E}) \sum(ET) \sum(Rf) - (\sum Inf) \quad (4)$$

Where: Re= Recharge, E= Evaporation, ET= Evapotranspiration, Rf= Runoff, Inf= Infiltration

2.7. Model Performance Evaluation

The following performance evaluation criterion was undertaken to assess the level of acceptability of the models:

Root Mean Square Error (RMSE) as provided in Eq. 5

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(X-Y)^2}. \quad (5)$$

Relative Mean Absolute Error (MAE) as provided in Eq. 6

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|X-Y| \quad (6)$$

i. Mean Absolute Percent Error (MAPE) as provided in Eq. 7

$$MAPE = 100 \times \frac{\sum_{i=1}^{n}(X-Y)}{\sum_{i=1}^{n}X} \quad (7)$$

ii. Nash-Sutcliffe Efficiency (NSE) as provided in Eq. 8

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}(X-Y)^2}{\sum_{i=1}^{n}(X-\bar{X})^2} \right] \quad (8)$$

Where; X = Observed value of the parameter being evaluated Y= Simulated value of the parameter being evaluated n = total number of observations i = numbers 1, 2, 3 …n. (Moriasi et al., 2015)

3. Results and Discussions

3.1. Yala Catchment Precipitation Analysis and Results

The periods of peak rainfall was experienced on the 4th year, 40th year, 52nd year, 67th year and 97th year with interval of 36 years, 12 years, 15, years, and 30 years. The peak over 2,250mm/year was observed in the years 1925, 1960, 1972, 1987 and 2018. The highest was recorded in the year 1987 with above 2,500mm/year. From the year 1987, the precipitation levels reduced and later increased in the year 2018 as shown in Fig. 2.

The trends from the year 1981 to 2024 in Kaimosi station confirmed that the periods of peak rainfall was in April and August. Temperatures were high in December through to February while lower limits were recorded in April through to August in each typical year.

3.2. Precipitation Intensity Duration Frequency

The optimal return period was established to be 10 years with a frequency factor of 1.5 as presented in Table 2.

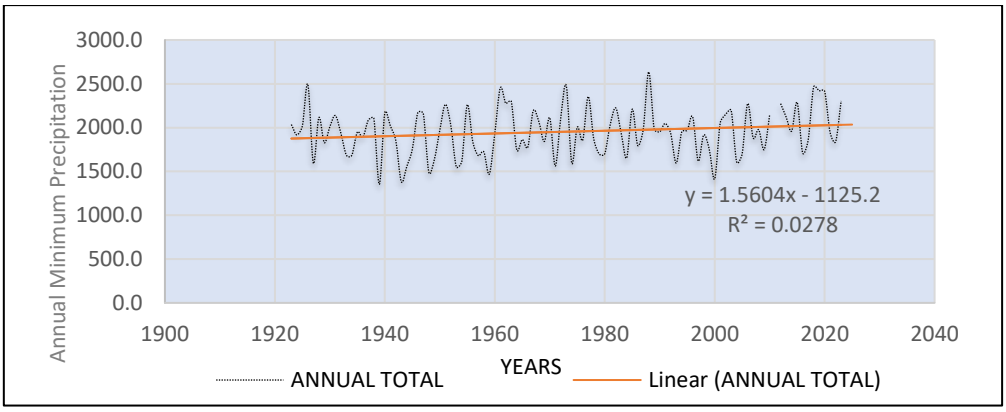


Fig. 2: Rainfall trends 1923-2023 (Kakamega metrological station)

Table 2: Return period and frequency in the catchment

Return Period	2	10	25	50	75	100
Frequency factor (kt)	-0.155	1.50	2.34	2.96	3.32	3.57

The period analyzed was from 2 to 100 years with respective frequency factors (kt). 24 hours rainfall intensities under different recurrence interval using Gumbel distribution was as presented in Fig. 5

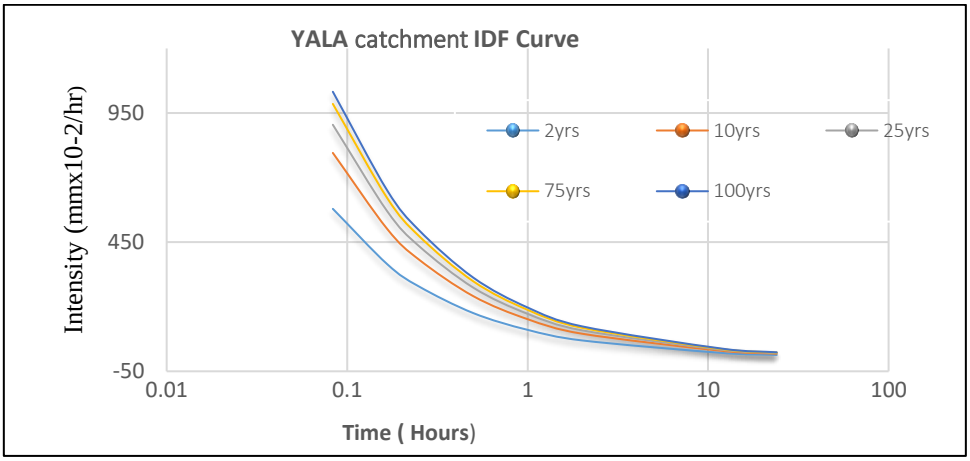


Fig. 3: Yala catchment IDF curve

The intensity duration frequency curves as shown in Fig. 3 established that the catchment experienced rainfall intensity from 9.7mm/hour within the first 10 minutes and declined to below 1mm/hour after 10 hours of storm. It was also evident that the return period of 10 years deviated less in intensity for 25 years, 75 years and 100 years establishing that consistent and reliable peaks could be experienced more often within 10 years in the catchment with variable intensity and period of rainfall events. The variability nature of rainfall observed in the catchment confirmed the results by the research done by Miima et al. (2025), where he also adduced that the catchment precipitation increasingly experienced impacts of climate change linking it to rainfall variability. The managers in the catchment while planning for hydrogeological infrastructure should consider an approximate recurrence of 10 years peaks of rainfall intensity in the catchment.

3.3. Analysis of Catchment Temperature Results

The temperature and soil moisture established a variation in the event of precipitation. Whereas while the temperature was reducing, the moisture increased. The data summary for observed temperature and soil moisture was as provided in Table 3.

Table 3: Summary of observed temperature and soil moisture

Variable	Range	Mean	Observation
Temperature (˚C)	17.84- 21.83	19.8	Moderate fluctuation, slight warming trend
Moisture (% VWC)	4.01-6.03	4.25	Gradual, steady increase

The Initial drop (21.83 → 17.84 ˚C) between Time = 1.0 and 3.0 suggested a cooling event possibly due to reduced solar radiation including sunset, shading, or cloud cover. After Time = 3.0, the temperature rises gradually to ~20.9 ˚C by Time = 14.0, suggesting re-warming, consistent with a diurnal cycle (morning warming after night cooling). Final readings (20.33 ˚C) stabilized, implying the soil profile reached a steady microclimatic equilibrium.

It was established that during rainfall events, the surface air temperatures at levels of 12cm above the ground and at -6cm below the ground falls to ~10˚C which was a deviation from the normal average of ~20˚C

and the temperature below the top soils layer stabilized at average limit of 3°C after a rainfall event.

Findings in this research established temperature-dependent soil moisture variation and infiltration trends where warmer temperatures enhanced infiltration, while colder temperatures reduced it. This was consistent with findings by Hillel (2014) in his publication in "Environmental soil physics", found that infiltration rates decreased by 30–50% in colder seasons due to reduced soil permeability.

3.4. The Soil Moisture

The volumetric soil moisture started at 0.4%, increased gradually to 5.3%. This increase was subtle averaging at Δ ≈ 0.9, but demonstrated consistency which suggested a slow soil wetting phenomenon, possibly from either: capillary rise or infiltration from a recent rainfall, evening condensation increasing near-surface soil water, or soil temperature drop reducing evaporation, allowing moisture accumulation.

The small fluctuation ranging at an average of ± 0.1, indicated stable soil conditions and good sensor–soil contact with no sudden spikes. Then moisture was also observed to stabilize at approximately 0.425m within a cubic unit of surrounding soil for regions with grass vegetation cover. This was assumed to be the point at which the molecule of water in the soil profile was retained and subsequently setting the infiltration process as presented in Fig. 4.

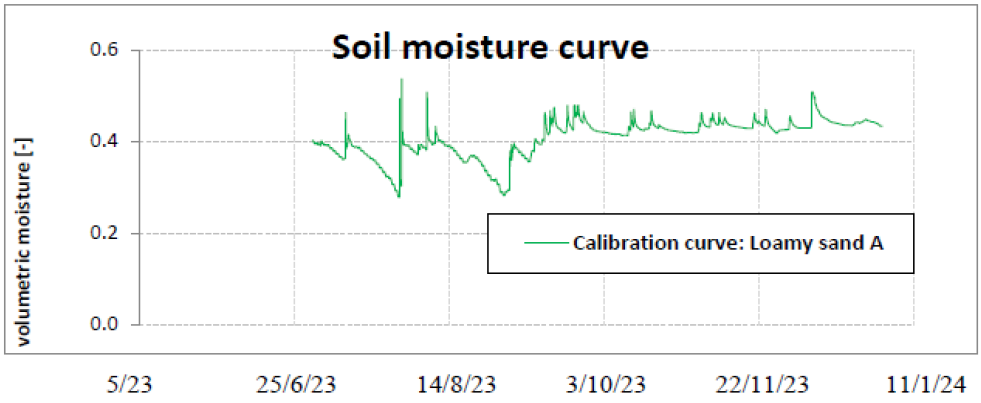


Fig. 4: Soil moisture curve

3.5. The Soil Moisture Curve Equation at the Vadose Zone

The real time moisture measured values were analyzed and moisture polynomial curve plotted and the trend gave an R^2 of 0.2853, while the linear curve gave R^2 of 0.361 as shown in Fig. 5

Though the analysis generated lower values of R^2, the study observed that the moisture variation was intermittent irrespective of time in the soil profile as shown in Fig. 5. The temperature had an inverse effect in the first 2,000 minutes and from 5,000 to 9,000 minutes, but in between 2,000 and 5,000 minutes, the moisture increased despite the increase in temperature. It was observed that the soil below 0.425m reached saturation level that any increase of unit energy due to increase in unit temperatures could not immediately change the state of the soil water molecule at that level thus steady increase in moisture.

The key findings outlined varied moisture increases or decreases in post-rainfall aligned with high infiltration rates. This study confirmed that cooler soil temperatures often accompany wetting events, implying that infiltration began to occur as a prerequisite for recharge which was consistent with Reynolds et al. (2002), where in their paper "The Soil Water Characteristic Curve: A Practical Tool for Infiltration Analysis.", provided methods to link volumetric soil moisture (VSM) measurements to infiltration rates and reported infiltration rates of 15 mm/hour for similar soils conditions with particular observation for different soil textures.

Another key observation was that the volumetric soil moisture increased gradually from 0.4%, to 5.3% with a subtle averaging at Δ ≈ 0.9, though demonstrating slow soil wetting phenomenon, possibly from capillary rise or infiltration from a recent rainfall, evening condensation increasing near-surface soil water, or soil temperature drop reducing evaporation, allowing moisture accumulation. This finding is consistent with finding by Waswa & Lorentz (2019), where they observed that an individual rainfall event yielded quick response to infiltration. They further observed that soil water response was dependent on the soil media condition at the time before and during the storm event that generated spatial infiltration, percolation and recharge levels with some flow responses being transient and discrete in nature.

3.6. Soil Water Infiltration and Recharge

The results shows that the moisture readings increasing from 4.0 to 5.3 % Volumetric water content (VWC) alongside modest soil-temperature variations (~17.9–21.8°C). Although it was a small moisture change, it gives useful insight into near-surface infiltration conditions as indicated in the Table 4 below;

Table 4: Moisture and temperature interpretation and relevance

Observation	Interpretation	Relevance to Recharge
Gradual moisture increase (4.0 → 5.33 %)	Indicates water input to the soil-from light rainfall, dew, or capillary rise.	Suggests infiltration has begun, a prerequisite for recharge
Temperature decreases (21.8 → 17.8 °C) then rises again	Likely marks a cooling event (evening or rainfall) followed by warming.	Cooler soil temperatures often accompany wetting events, meaning infiltration is occurring.
Stable moisture after Time ≈ 12 – 16 h	The soil reaches a near-steady water content	Suggests infiltration slowed and water redistributed within the profile.

Rainfall wetted the surface as detected by TMS4 with rise from 4.0 to over 5.3 % VWC. The moisture increase recorded at shallow depth shows the initial stage of soil wetting occurring, but later stages depended on soil permeability, texture, and Soil-water holding capacity, depth to groundwater, duration and intensity of the wetting event. Though Percolation moved water downward through the unsaturated zone, recharge occurs when percolated water reaches the saturated zone (water table), the recharge efficiency could not be substantively concluded because the soil was still below field capacity (~0.25 m^3/m^3 for loam) (Horton, 1940). Below field capacity, gravitational drainage is limited and for recharge to start, soil pores must fill sufficiently to allow free drainage. While plotting the soil water infiltration against time in hours, the infiltration rates curve intersected at 975hours after 2,200mm of incremental moisture with infiltration rate of 400 units (fp-Fc). This trends confirmed Horton principle on the rates of increase of precipitation against infiltration. Although the study observed that the curve could not present a constant point in line with Horton's curve due to the fact that the near surface soil layer experienced fluctuation in moisture as a results of variability of intensity and period of precipitation events.

3.7. Infiltration Capacity

The study analyzed the infiltration capacity in the catchment and Fig. 6 shows the curve and the derived equations.

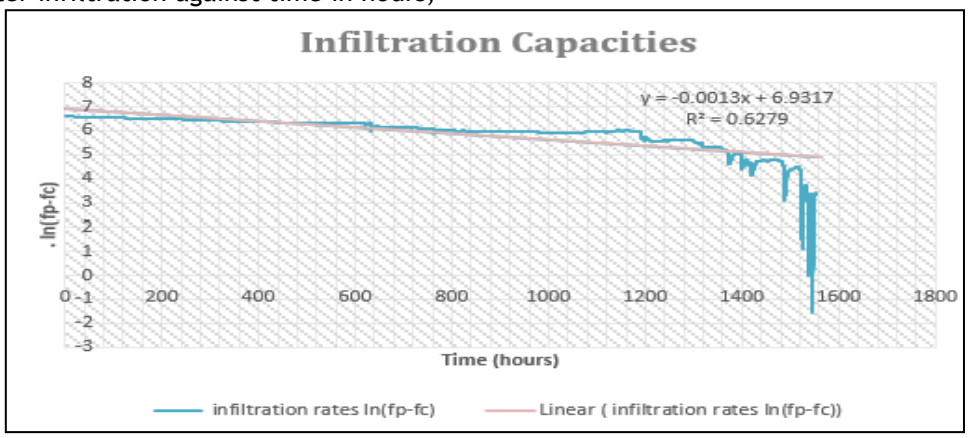


Fig. 6: Infiltration capacities curve 1

The infiltration capacity curve in Fig. 6 provided R^2 of 0.62 and the respective curve equation values were used to customize Horton's model to the catchment as derived in Eq. 9 where:

K (slope of the graph) was 0.0013 and Ln (fo-fc), the Y-intercept= 6.9317, therefore;

$$F_p = 702.513434 + 1024.2337\, e^{-0.0013t} \quad (9)$$

For upper mid catchment Horton's equation was as outlined in Eq. 10 where the K (slope of the graph) was 0.0008 and Ln (fo-fc) Y- intercept was 5.9556, therefore;

$$F_0 - F_c = e^{-5.9556t} = 385.9084$$

$$F_p = 702.51 + 385.91\, e^{-0.0008t} \quad (10)$$

The soil water infiltration was found to be higher at the beginning of a storm and experienced an exponential decay with respect to time as shown in Fig. 6 confirming Horton's model. Perturbation of Horton's equation using the catchment values derived i.e. k, ln, f0 and fp derived Eq. 9 and 10. When precipitation was plotted against infiltration, the graph provided a linear correlation with R2 of 0.7295 and equation y=0.3159x+5.9663 as presented in the Fig. 7 below.

These results established that precipitation linearly correlated with infiltration and that infiltration corresponded to transient percolation which sets the recharge process through the vadose zone as discussed in section 3.5. The soil infiltration and percolation in this study established that effective depth at which recharge commences was at 0.425m which is 42.5cm falling within the range as opined by Scanlon et al. (2002) where in their study, while estimating groundwater recharge utilizing TMS4 sensors for soil moisture monitoring, observed that high volumetric soil water content in a period of more than 48 hours at 30-50cm indicated effective initial recharge.

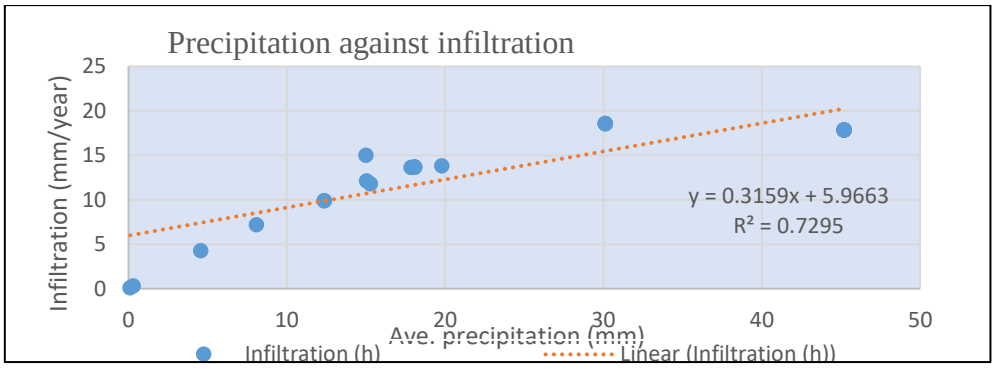


Fig. 7: Precipitation against infiltration.

On the other hand, the results demonstrated the influence of catchment environmental conditions including temperature and weather on infiltration and recharge. Rainfall intensity and duration also played a significant role, with heavy rainfall enhancing infiltration. These findings aligned with previous research, emphasizing the importance of soil properties and environmental conditions in determining water movement Reynolds et al. (2002).

Further in this research, infiltration of soil water was found to be higher at the beginning of a storm and had an exponential decay as the time lapses as shown in Fig. 6 partly confirming Horton's model though the definite point for infiltration was not fixed due to variation in climatic conditions including temperatures, rainfall and soil texture.

3.8. Model Uncertainty and Validation

Evaluation of performance was undertaken using the formula in Eq. 4, 5, 6, 7 and 8. The level of performance was established using precipitation and infiltration data. The performance criteria recorded MAE of 1.12, MSE=1.17, RMSE=3.13, MPE=-0.16 MAPE =0.16 and NSE= 0.92 as outlined in Table 5.

Table 5: Model Performance evaluation

	Measure	Acceptable levels	Model
1	MAE	0.0 to ∞	1.12
2	MSE	0.0 to ∞	1.17
3	RMSE	0.0 to ∞	3.14
4	MPE	< 0.0 to ∞	-0.16
5	MAPE	0.0 to ∞	0.16
6	NSE	0.50 < NSE < 1	0.92

The performance evaluation established that the model performance criteria of evaluation were in the range of acceptable levels. The model results was therefore validated to be reliable with minimal outliers.

3.9. Regression Analysis of Recharge in the Catchment

Analysis shows that R^2 was 0.72 with adjusted R^2 giving 0.67. These results established that the relationship at the upper vadose zone could be reliably predicted with infiltration from precipitation which demonstrated a direct effect on complex recharge process. This results conformed to the recommendation by Kiluva et al. (2022) which stated that the complexity of any watershed compelled one to use simplification while conducting the study. Table 6 shows the analysis results.

Table 6: Regression analysis of recharge in the catchment

#	Statistical regression output	Values (Figure)
1	Multiple R	0.8460036
2	R Square	0.7157221
3	Adjusted R Square	0.6722438
4	Standard Error	58.390074

As outlined in Table 6, the statistical regression results for recharge in the catchment gave multiple R to be 0.846, R^2 was 0.716 and adjusted R^2 was 0.672 meaning that the regression model variability was within acceptable range and demonstrated that the recharge process though complex but the relationship could be established with simple definite parametric analysis of the system.

3.10. Recharge Prediction of Trends

Recharge predicted trends as shown in Fig. 8 demonstrated that the hydrogeological system was complex with varying recharge levels against time. The variability nature of recharge aligned with the variability nature of precipitation including rainfall amounts and intensity in the catchment overtime as was adduced by linking this phenomenon to climate change. It was observed in the normal prediction plots aligned well from 0 to 75th sample percentile and increased steadily from 75th to 90th then stabilized. The recharge in the catchment hydrogeological regime was transient with expected outliers and skewness as a result of state of parametric changes.

The analyzed results did not show accurate and reliable forecast in determining the flow trends for next succeeding period. This confirmed the complexity of the hydrogeological regime that requires sound hydrological flow model to simulate the flow regime in the catchment.

4. Conclusion and Recommendations

4.1. Conclusion

The results indicated a subtle soil wetting phenomenon (ΔVSM ≈ 0.9%), with VSM increasing from 4%

to 5.3% and stabilizing at 4.25%, coupled with modest soil temperature variations (~17.84–21.83°C). These findings suggest initial near-surface infiltration conditions moderate water content in the events of precipitation, but after an average period of 48 hours the soil moisture remained below field capacity (~0.25 m^3/m^3 for loam), limiting gravitational drainage. These results highlighted the soil's ability to absorb and retain water, which could be critical for crop farming, irrigation planning and groundwater infiltration and recharge."

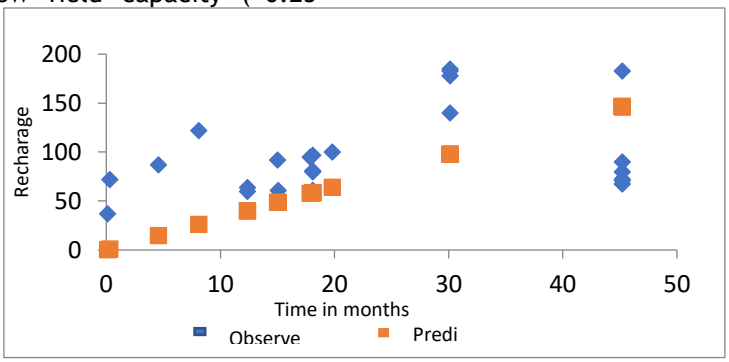


Fig. 8: Recharge trends

The TMS4 sensor data revealed significant variations in infiltration and groundwater recharge potential across the TMS4 sensor sites. General observation was that there was varying infiltration and recharge potential, particularly after rainfall events, where there was to be prolonged moisture retention between 33 to 48 hours. These findings underscores the importance of site-specific soil and land management practices to enhance water infiltration and support sustainable groundwater resources."

This study results established a temperature-dependent soil moisture variation and infiltration trends where warmer temperatures enhanced infiltration, while colder temperatures reduced it. The key findings was that cooler soil temperatures often accompany wetting events, implying that infiltration begins to occur as a prerequisite for recharge. The surface air temperatures at levels of 12 cm above the ground and at -6cm below the ground, reduced from the normal soil moisture temperatures to below 10°C while the temperature below the top soils layer stabilized at between 2 - 3°C after the rainfall event.

The temperature drop then rise was observed with an inverse effect in the first 2000 minutes and from 5000 to 9000 minutes, while between 2000 and 5000 minutes, the moisture increased despite the increase in temperature. This was attributed to rainfall or surface cooling event linked to infiltration. The study underscored the critical role of near-surface soil moisture dynamics during the first 2000 minutes of precipitation in determining infiltration rates and recharge potential.

Soil moisture stabilized approximately at 0.425m (42.5cm) within a cubic unit of surrounding soil beyond which any increase of heat from increasing temperatures could not immediately change the state of the soil water. The Observed VWC (0.05–0.06 m^3/m^3) Indicated partly dry soil and that infiltration was initiated but the soil unit remained generally unsaturated. Statistical regression yielded an R^2 of 0.72, confirming the reliability of the analysis.

4.2. Recommendations

4.2.1. Catchment Water Management

This research proposes sustainable and relevant catchment protection and management strategies including improved agricultural practices, increased vegetation cover, reforestation to improve catchment micro-climate, increase rainfall, reduce evapotranspiration and evaporation which will result to improved infiltration and recharge to water bodies.

Catchment management and runoff mitigation measures including development of infrastructure like gabions, ditches, dams and good drainages when considered will enhance protection and conservation of wetland and riparian areas.

4.2.2. Monitoring

Monitoring of deeper soil layers including installing sensors at deeper than 50 cm would provide useful insights into groundwater recharge.

4.2.3. Future Research

The research observed near surface soil dynamics and proposes assessment of water table response to recharge for comprehensive hydrogeological understanding.

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